REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 29-02-2012

2. REPORT TYPE: Final

3. DATES COVERED *(From - To)*: 1 DEC 2009 - 30 NOV 2011

4. TITLE AND SUBTITLE

Development of Microplasma Arrays for High Efficiency Lighting Tiles

5a. CONTRACT NUMBER: FA9550-10-C-0022

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Park, Sung-Jin

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

EDEN PARK ILLUMINATION, INC.
903 N COUNTRY FAIR DR
CHAMPAIGN IL 61821-3259
(217) 403-1866

8. PERFORMING ORGANIZATION REPORT NUMBER

EPI-2012-01

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

USAF, AFRL DUNS 143574726
AF OFFICE OF SCIENTIFIC RESEARCH
875 N. RANDOLPH ST. ROOM 3112
ARLINGTON VA 22203
MATTHEW J. SLOWIK (703) 696-1086

10. SPONSOR/MONITOR'S ACRONYM(S)

AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-OSR-VA-TR-2012-0824

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for the public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Microplasma lamps with high luminance and a thin, flat form factor have been developed and fabricated in sizes up to 1 sq. ft. (930 cm2). The luminous efficacy of panels having a microcavity structure was improved to beyond 30 lumens/W in Xe/Ne gas mixtures.
A wide variety of new lighting applications are now available due to lightweight construction and panel thicknesses of less than 5 mm. Because microplasma lighting photometric performance is independent of temperature, the devices are instant on/off. The glass enclosure serves as the lamp structure, allowing minimal fixturing (when compared to conventional lighting systems) which is ideal for high space utilization.

15. SUBJECT TERMS

STTR Final Report, Microplasma, Lighting, flat lamp

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Sung-Jin Park
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	14	19b. TELEPHONE NUMBER *(include area code)*
U	U	U			217-403-1866

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Air Force STTR Phase II
Final Report:

Development of Microplasma Arrays for High Efficiency Lighting Tiles

Period of Performance:
12/1/2009 through 11/30/2011

Sung-Jin Park, PI
EDEN PARK ILLUMINATION, INC.
903 N. Country Fair Drive
Champaign, IL 61821

Contract Number: FA9550-10-C-0022

February 2012

TABLE OF CONTENTS

EDEN PARK ILLUMINATION
FINAL REPORT

I. **PROJECT SUMMARY**: EDEN PARK ILLUMINATION, INC. and the University of Illinois have formed a team to pursue the demonstration and commercialization of large arrays of microcavity plasmas capable of producing white light panels with luminous efficacies above 30 lumens/W. This project will demonstrate the ability of arrays of microplasmas to yield flat lamps of high efficiency, luminance, and color rendering index suitable for general lighting. Microplasmas represent a new technology that we expect to be disruptive to the lighting industry because their properties (low temperature and atmospheric pressure operation, and specific power loadings of kW/cm^3) have no parallel in conventional, macroscopic plasmas. A team comprised of leading researchers and engineers from the University of Illinois and Eden Park Illumination will aggressively pursue lamps employing *molecular emitters* of high radiative efficiency to realize lamps having efficacies of *at least* 30 lumens/W, and luminance values above 500 lumens. A successful program will have a significant impact on the energy consumption of lighting in the U.S. by providing non-toxic, ballast free, lightweight, and efficient lamps with radiating areas >200 cm^2.

II. **GOAL OF PROJECT**: The primary goal of this program is to demonstrate arrays of microcavity plasma lamps, and having a radiating area of 200 cm^2 or more, that generate visible emission with a luminous efficacy of *at least* 25-30 lumens/W. A secondary objective is the design of a fully-addressable array that is also 100 cm^2 in radiating area.

III. ACHIEVEMENTS

A. Summary of Phase II Milestones

The second phase of this STTR program was (we believe) very successful as all of the goals set forth in the original proposal to AFOSR were achieved. The most significant of these accomplishments are:

1. Microplasma light panels as large as 12×12 in^2 (930 cm^2) have been fabricated and demonstrated successfully.
2. Low-cost, high-volume fabrication techniques for the light panels up to 12×12 in^2 has been established
3. Optimization of driving circuits has increased the power conversion efficiency to 87% and the power factor to 98%.
4. The luminous efficacy of 6×1.5 in^2 panels having a microcavity structure was improved to beyond 30 lumens/W in Xe/Ne gas mixtures.

In short, we are pleased to report that all the goals proposed in the Phase II proposal were surpassed. The collaboration between EPI and the University of Illinois has proven to be efficient and rewarding, and this productive partnership will be continued after this program. A more detailed accounting of the work completed in the Phase II program follows.

B. Description of Work Completed in Phase II

i. Large Scale Microplasma Lighting Tiles

Flat, thin and lightweight lamps providing spatially uniform and dimmable illumination from active areas as large as 930 cm^2 were successfully developed for general illumination and specialty applications. Comprising an array of low-temperature, nonequilibrium microplasmas driven by a dielectric barrier structure and operating at pressures of typically 400–700 Torr, these lamps have a packaged thickness < ~5 mm and yet produce luminance values beyond 15,000 cd/m^2 with a luminous efficacy approaching 30 lm/W. After the continuous efforts on new structure development, our third generation lamps, presently in limited production, offer a correlated colour temperature in the 3000 – 6000K interval and a colour rendering index higher than 80. Current lamps employ Xe_2 ($\lambda \sim 172$ nm) as the primary emitter photoexciting a mixture of phosphors, and the pressure dependence of the wavelength-integrated fluorescence from the electronically excited dimer has been investigated with a vacuum ultraviolet spectrometer. In contrast to other promising lighting technologies, the decline in luminous efficacy of microplasma lamps with increasing power delivered to the lamp is small. For a 6×6 $inch^2$ (~ 225 cm^2) lamp, efficacy falls < 16 % when the radiant output (luminance) is raised from 2000 cd/m^2 to >10 000 cd/m^2.

Throughout this program, emphasis was placed on continuously improving the performance of the structure of our lamps. Figure 1 shows the cross-section of a representative lamp structure fabricated under this AFOSR program. This design presumes the confinement or partial confinement of low temperature, nonequilibrium plasma within the space having a characteristic dimension $\lesssim$ 1 mm. The lamp incorporates an internal spacer structure fabricated from various materials (currently from glass). Areal capacitance is the primary drawback of such a structure and patterned electrodes such as those shown in Fig. 1 are preferred.

All of the lamp designs being pursued at Eden Park are solder glass-sealed with a Bi-based (i.e., lead free) frit and thorough degassing of the completed structure prior to backfill is

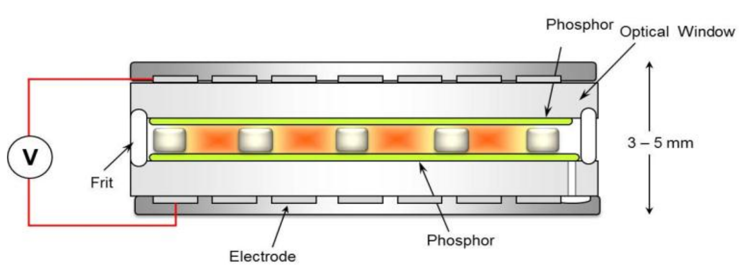

Fig. 1. Cross-sectional diagram of a representative single-sided microplasma lamp

essential to attaining maximum performance and extending the lifetime of the lamp. Films of a custom RGB phosphor mixture are printed on the interior surface of both the glass window (top) and the rear plate of both lamps of Fig. 1. It is also clear from the figure that the overall thickness of the lamp "engine" can be as small as few millimeters. Most of the lamps manufactured at present are single-sided designs with 1.1 mm thick windows and an overall (packaged) lamp thickness < ~5 mm. As shown in Fig.2, the current fabrication processes for the microplasma lamp (Phoenix lamp) product are compatible with low cost, volume production by a series of automatic tooling. Further improvements in the quality of the end product and in the ease of conversion to production will be realized with the replacement of some of the key processes with new processes such as tube-free backfill, glass molding and spray phosphor coating process. Figure 3 is a photograph of a microplasma lamp, having a radiating area of 12" x 12" (930 cm^2), that was filled with a Xe/Ne gas mixture. Overall panel dimension and weight of the panel itself is 12.5" × 12.5" and ~ 950 grams, respectively. The luminance output of the lamp when driven by a 40 kHz bipolar pulses waveform(> 2 kV) is as much as 15,000 cd/m^2 (4,000 lumens) and the luminous efficacy of the panel is beyond 20 lumens/W.

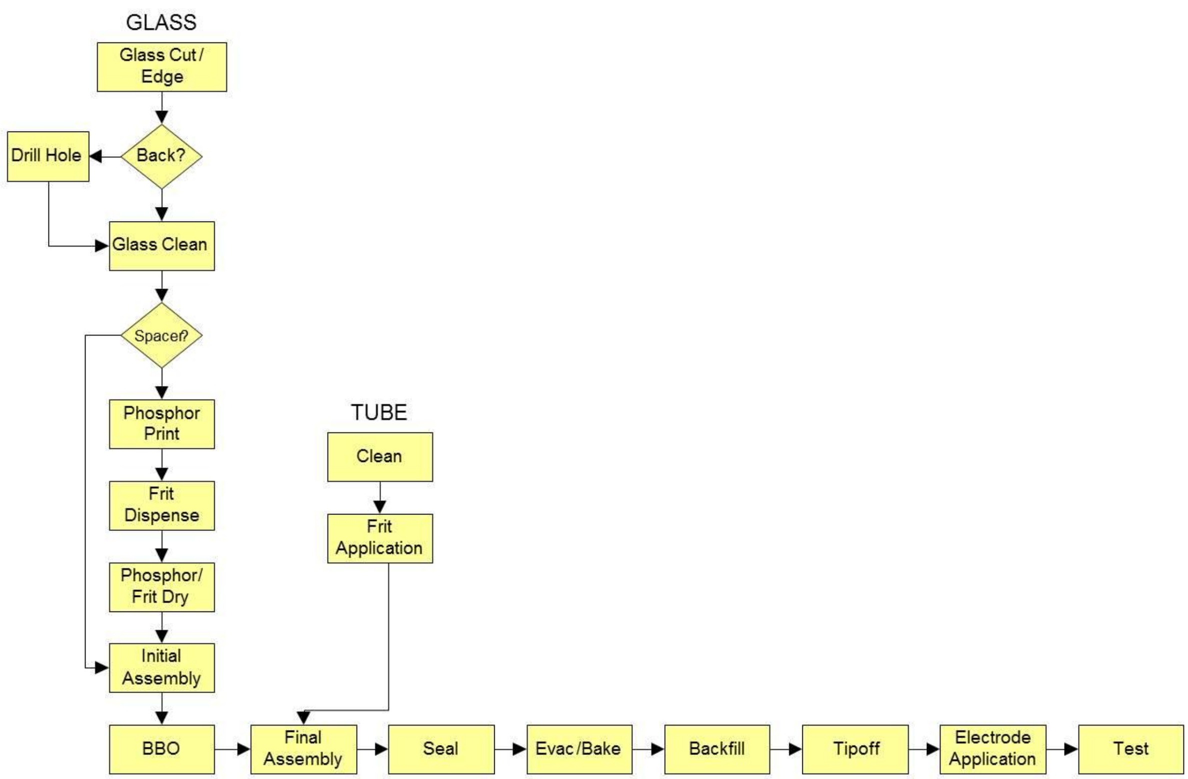

Fig. 2. Flow diagram of microplasma lamp fabrication processes

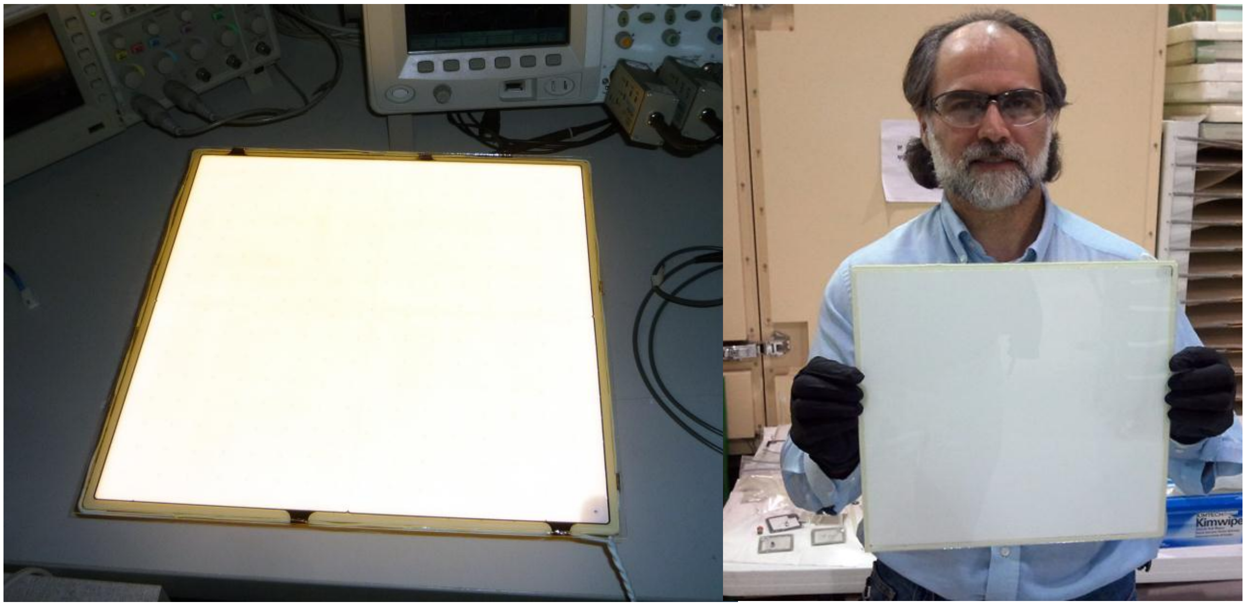

Fig.3. Photographs of a microplasma lamp having an active are of 12 × 12 in.^{2} (930 cm^2). A photograph at the left side shows operation of the lamp at 15 kHz and in the total gas pressure of 400 Torr of Xe/Ne mixture.

ii. Progress in Lamp Performance

Figure 4 shows a photograph of 6 × 6 sq. in. (~225 cm^2) phoenix lamps currently in limited production. Capable of generating dimmable luminance values beyond ~10,000 cd/m^2, the current generation of lamp has a luminous efficacy (as measured at ~600 lm with a calibrated 40 in. dia. integrating sphere) approaching 25 lumens/W. The specification of these 6 × 6 sq. in. lamps was summarized in Table 1.

Fig. 4. Photograph of demonstration units for phoenix lamp (6 × 6 in.^{2}). It is fully dimmerable, and standard operation of this lamp has a light output with 600 lumens.

Mechanical Specifications	
Dimensions (lamp only as shown above)	Inches: 7.5” x 6.5” x 0.46” (cm: 19.05 x 16.5 x 1.17)
Weight	0.20 kg (0.51lb.)

Environmental Specifications	
Environment	Dry locations only
Operating ambient temperature range	-20°C to 60°C (-4°F to 122°F)
Surface temperature	50° - 60° C

Electrical Specifications	
Cables	Up to 72 inches
Voltage	120 V, 60 Hz
Current	0.3 A
Power consumption	35 W
Listings	UL, ETL (pending)
Driver	Full bridge resonant power supply

Photometric Specifications	
Luminous flux	600 lm dimmable to 10%
Luminance	10000 cd/m^2
Light source	Microplasma
CCT	3000 K and 4100 K
CRI	82
Life	50,000 hr
Efficacy (lamp)	22 lm/W
Lighting Uniformity	+/- 5% across lamp surface

Table 1. Specification of 6 × 6 sq. in. Phoenix lamp.

As shown in the table, the optical fluence emitted from the lamp surface is remarkably uniform. Spatially-resolved radiometer measurements show the luminance to be uniform over the entire ~ 225 cm^2 lamp surface area to within ±5%. With regard to the colorimetric performance of the lamps, considerable effort devoted to testing phosphors from multiple sources has resulted in the ability to tune the color point of the lamp while tracking the Planckian locus. Correlated color temperatures (CCTs) ranging from ~2900 K to ~6000 K can now be specified reproducibly while maintaining a color rendering index (CRI) of at least 80. Introducing an additional phosphor into the standard, three component mixture has been found to be effective in boosting the CRI above 80. Therefore, lamps can be produced with virtually any color point within the color gamut typically available to plasma display panels. Unit-to-unit color variation for 65 production Phoenix lamps was confined to within a 1-step MacAdam ellipse (Figure 5). Color variation is also maintained to a 1-step ellipse over the complete operating temperature, the full-dimming luminance range, a broad angular distribution, and across the emissive surface of the lamp. The angular intensity distribution produced by a 6 × 6 sq. in. microplasma lamp has been measured and it is compared with that of a commercial LED light panels which has very similar form factor with the microplasma lamp. In Figure 6, angular intensity distribution for the microplasma lamp follows a Lambertian profile (represented by the black solid curve) and it indicates very uniform angular distribution over the LED flat panel which has narrower intensity distribution. The LED flat panel exhibits asymmetric distribution because of the optical components installed on the LED chips. Figure 7 provides simple comparison for the light quality of microplasma lamp to that for conventional lamp products. As shown in Fig 7 (d), microplasma lamp (even in a Bezel) has a very thin form factor as compared to other lamps such as fluorescent and LED lamp

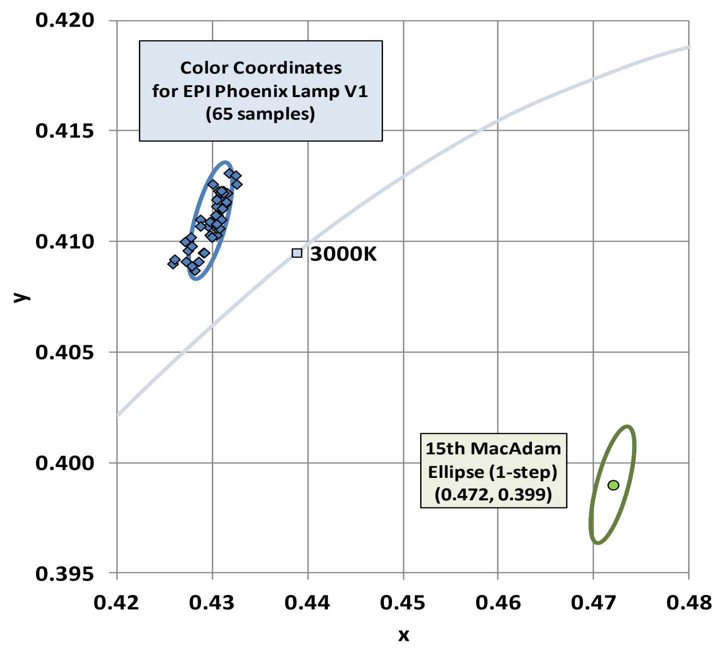

Fig. 5. Measurement of unit-to-unit color variation for 65 phoenix lamps having the CCT of 3000K. Color points are located at the Chromacity (CIE coordinate) diagram.

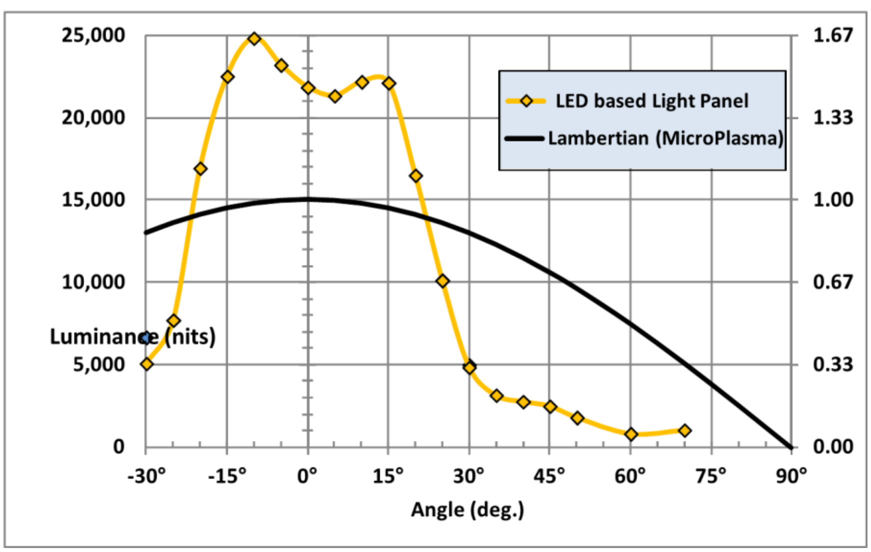

Fig. 6. Angular intensity distribution of a microplasma lamp (black solid line) and a commercial LED based flat light panel (yellow line).

(a) (b) (c) (d)

Fig. 7. Photographs of microplasma lamp in a geometry of under-counter lighting. Each "Demo Cubes" indicates the typical lighting sources which are commercialized: (a) Fluorescent Lamp (b) and (c) LED lamps having higher and lower color temperature (d) Eden Park microplasma lighting tile.

products. Also, the light distribution and quality of color temperature are superior as much as the fluorescent lamp and no glare or dark shade was found compared to the other three lamps. At this moment, the bill of materials (BOM) for the microplasma lamp is expected to be in the middle of LED fixtures and mercury contained fluorescent lamp.

The luminous efficacy of the 6" x 6" lamp falls by < 16% when the luminance is raised by more than a factor of five to values beyond 10,000 cd/m^2. These data are representative of those obtained from testing literally scores of lamps. The most recent generation of 6 × 6 sq. in. lamps exhibits a "droop" of < 10% when the luminance is increased from 2000 cd/m^2 to > 10,000 cd/m^2. These results indicate that the variation of the cumulative rate for all Xe_2^* excimer destruction process (such as superelastic collisions and excited state-excite state interactions) with rising power deposition into the plasma is no faster than linear. Also, the color temperature of the lamp over the luminance value is very stable that it shows variation of ± 50 K when the luminance is increased from 2000 cd/m^2 up to 10,000 cd/m^2.

iii. Optimization of Pulsed Power Supply Design

The efficacy of the lamp is critically dependent on lamp structure and voltage driving conditions, and by the optimization of driving circuits. For the lamp structure developed at Eden Park Illumination and the University of Illinois, considerable effort has also been devoted to optimizing the drive voltage waveform and the size of the power supply. The best performance of the lamp to date was achieved with high voltage, bi-polar pulses having a fast risetime. Fast and high voltage pulses are necessary to decrease impedance losses and to obtain an electric field of sufficient strength during the short span of the pulse width so as to optimize the E/p ratio in the plasma. The highly inductive basic power supply typically has a lower limit of pulse risetime of ~1 microsecond. Better performance (higher efficacy) of the lamp is observed through faster rise-time pulses, closer to ~100 nanoseconds.

The fast pulse power circuits developed at Eden Park are either a full bridge switching circuit with a series of power FETs or a H-bridge architecture using high-voltage insulated gate bipolar transistors (IGBT). This gives the flexibility of providing different drive characteristics for the positive and negative pulses thereby creating asymmetric pulses if needed. A recent optimization of the circuits leads us to get the improvement of the supply performance that efficiency increased from about 75% (current product supply values) to 87%, and the rise time was decreased below 100 ns. Furthermore, power factor increased from 0.5 to 0.98.

Fig.8. Photographs of power circuits for the 6 × 6 in.^{2} microplasma lamps. One at the left end is the original circuit developed in 2008, and circuits to the right side shows the progressive improvement of power circuits to achieve size reduction and high efficiency.

iv. Microcavity Assisted High Efficiency Lamp

The lighting technology was developed and patented at the University of Illinois and works by confining the gas discharge inside the lamp into thousands of cavities formed into the glass structure. This confinement allows the lamp to operate at higher pressures than conventional cold plasmas which enables greater efficiencies to be achieved than with lower pressure xenon discharge lamps. Inside a running lamp, xenon atoms in the discharge form molecules called diatomic xenon(Xe_2) which emit VUV radiation that is converted to white light by the phosphor covering the inside of the lamp. The efficiency of the lamp depends on the ability to generate the diatomic xenon, and this process is helped with increasing pressure since there are more xenon atoms per volume that can interact. However, typical discharges form arcs or streamers at higher pressures due to the low thermal conductivity of the xenon gas. The microplasma technology is what allows the lamp to operate at higher pressures in a stable manner thereby achieving higher efficiency of UV production. Figure 9 shows a cross section of the glass envelope making up the lamp structure. The microcavities are etched into the glass

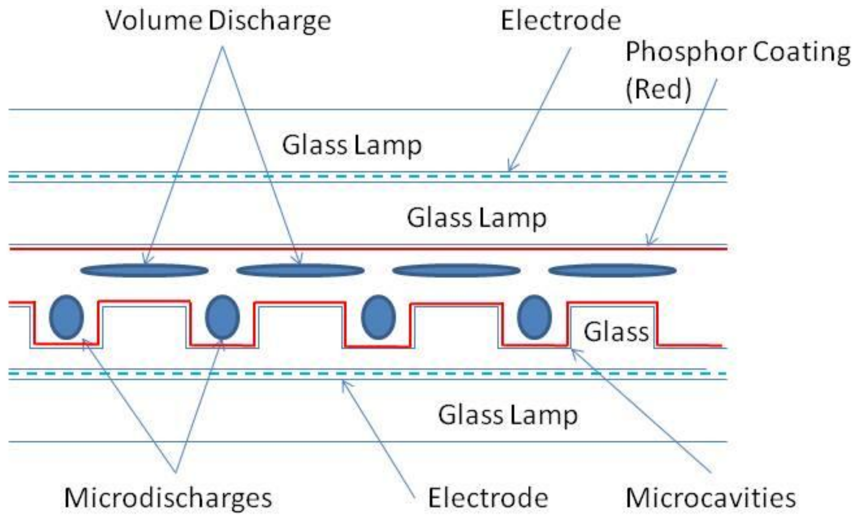

Fig. 9. Cross-sectional view of the flat panel lamp showing the incorporation of microcavities inside the glass envelope.

structure by micropowder blasting techniques before the application of phosphor and before the lamp is assembled. An additional benefit to the structure shown in Figure 9 is that the electrodes that supply power to the lamp are outside the gas discharge region. The lamp in this configuration works as a dielectric barrier discharge which results in projected lifetimes of >50,000 hours. Keeping the electrodes away from the gas discharge prevents metal sputtering which is the major contributor to the limited lifetime of standard fluorescent lamps, arc lamps (street lamps, high-bay lamps, etc.), compact fluorescent lamps, metal halide lamps and tungsten filament lamps.

Continuous efforts have been made for the research and development of the new lamp structures which will lead to higher efficacies. In particular, we have developed a new lamp structure, so called "microcavity assisted long gap lamps". From this structure, we have achieved the improved luminous efficacies up to ~35 lm/W (surpass the goal of 30 lm/W in this program!) at an area of 60 cm^2, and the luminance of the lamp was up to 6000 cd/m^2. This lamp is sustained by the combination of long gap (~30 mm) discharges and microcavity array plasmas which especially generated at the beginning of each pulse cycles. Microcavity plasmas are formed to create strong electric field around the long gap discharge electrodes and induce electron heating which initiates volume discharges across the lamp. In this structure, the geometry of microcavity array is very important for the stable operation and uniformity of the plasma. The microcavity structure was sandblasted to 1-3 mm in diameter on the rear plate of the lamp, and final diameter of these microcavities after lamp fabrication is ~20 % smaller to that of original diameters due to the thick phosphor layers coated inside the cavity. The diameter of microcavities is determined by the gas pressure inside the lamp. As we described earlier, the performance of the microcavity plasmas are also dependent on the driving condition of power supply and it is critical to be driven by as short as pulses (close to hundreds of ns). More experiments are aimed at improving the lamp uniformity and increasing the luminous output along with continuous increase of luminous efficacy. Figure 10 shows the operation of the microcavity assisted long gap lamp having an active area of 6" × 1.5". In particular, this new microcavity structure can create a series of different electrode designs and geometries. For an example, figure 11 shows a microcavity electrode design results in a lamp shape of "donut" without losing either luminous efficacies or light output, and it can be applied as a specialty illumination source for professional photography.

Fig. 10. Photographs for a new structure "microcavity assisted long gap lamp" (6×1.5 in.^{2}) and (right) a portion of phosphor-coated microcavity arrays on the rear plate of the lamp.

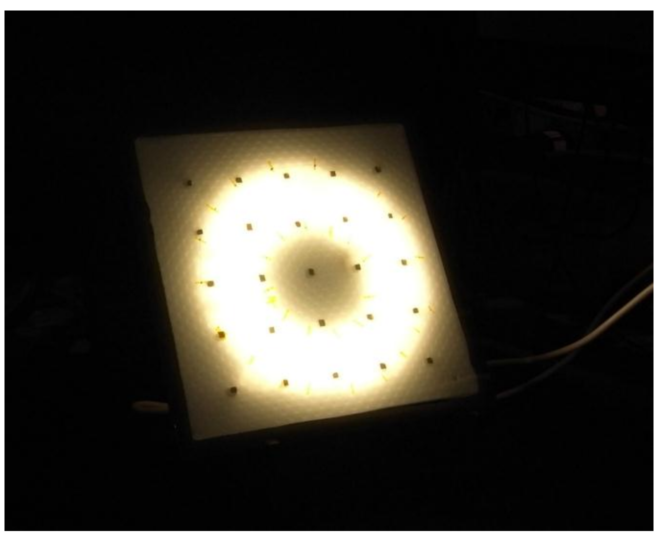

Fig. 11. Photograph for the operation of a highly efficient microcavity lamp having a shape of "donut" which having an outer diameter of 4 inches.

In summary, this AFOSR STTR Phase II program has been successful in that the luminous efficacy and lamp scale requirements were more than met. We intend to improve the lamp performances continuously to satisfy the specifications required for specialty and general illumination.

C. RESULTS

The optimization of lamp parameters (structure, scale, efficiency, and light qualities) is expected to raise this value significantly. Because of the form factor of microplasma lighting technology, the efficiency of Eden Park lamps in delivering a specified illumination level (e.g. foot-candles) to a surface rivals that of other technologies citing higher lamp efficacies but limited by poor utilization efficiencies. Furthermore, flat microplasma lamps are free of the requirements for auxiliary optics to efficiently extract light from the source, or diffusers intended to partially homogenize the illumination from an ensemble of point or cylindrical sources.

By the support of AFOSR, this technology opens new doors for lighting and Eden Park has recently built several under cabinet, chandelier, and ceiling tile “demos” to illustrate the versatility of the technology.

Fig. 12. Photographs of microplasma tiles which demonstrate their potential and versatile uses as a new lighting technology.

D. PROJECT STATUS AND PLAN

All the research and development cited above occurred as scheduled and the target goals we have previously set were met and surpassed. We are now in the phase of commercialization of these lighting tiles, and mass production planning followed by further process development. We were already approached by several lighting companies and designers, and product development processes are initiated according to the specification requested by potential customers. Also, our effort will focus on continuous improvement of the luminance efficiency and technical development for the new lighting applications such as specialty or UV lightings.

IV. RESEARCH PERSONNEL

A. Eden Park Illumination
Dr. Sung-Jin Park (PI), Jeffry M. Bulson (VP for Development), Dr. Cyrus M. Herring (VP for Research), Jeffrey Putney (Design Engineer), David DeHeven (Process Engineer) Dr. Walter Mason (Material Scientist), Youngwha Kim (Intern), Kyle Moon (Intern)

B. University of Illinois (Subcontract)
Prof. J. Gary Eden (Co-PI), Dr. Jin Hoon Cho (Postdoc), Dr. Seunghoon Sung, Jekwon Yoon, Min Hwan Kim (Graduate Students), Inchan Hwang (Researcher)

V. PUBLICATION

1. J. G. Eden, S.-J. Park, C. M. Herring and J. M. Bulson, “Microplasma light tiles: thin sheet lamps for general illumination,” *J. Phys. D.*, 44, 224011, 2011.

Some results obtained from this program are being temporally withheld from publication because of the sensitivity of the information with regard to commercializing this technology.